THE VARIATIONS OF GLACIERS.

THE great interest which the physical study of living glaciers has to the geologist is the light it may throw on causes producing, and conditions prevailing during, the Ice Age. One of the habits of living glaciers bearing most directly on the Ice Age is the variation continually occurring in their length, thickness and velocity of motion. All students of glaciers have collected reports and made observations themselves on the advance and retreat of the ends of particular glaciers, but it is only within about twenty years that anything like systematic work has been done in getting together records which enable us, in some cases, to exhibit roughly the variations in the extent of certain glaciers for three hundred years, during which period there has been quite a number of advances and retreats; observations since the fifties give us a fair record of the movements of some Swiss glaciers.

What are the causes of these variations? The answer of course is that they are meteorological, for it is quite evident that the extent of a given glacier depends on the snow-fall and the rate of melting; the ice continues to flow down its valley until it is all melted away. Anything that increases its velocity will make it flow further, and anything that increases its rate of melting will cut it off shorter. But which of these factors has been most important in determining the changes which have actually occurred? M. Forel has argued ably[1] that it is the change in velocity. He has shown that glaciers have varied very much in extent when there has been no great change in the rate of melting; that this has been due to a change in the velocity, which in its turn depended on a change in snow-fall. If this proves to be universally the case we have the following interesting application to make to the ice of the Ice Age: If the

[1] Bibliotheque Universelle de Geneve, VI., pp. 5–49, 448–460.

floods which occurred at the time when the ice-sheet was at its maximum (*i. e.*, when the melting area was greatest), were stronger than those which occurred later, we may infer that the retreat of the ice was due rather to a diminution of the snow-fall than to an increased rate of melting, brought about by a warmer climate; whereas, if the stronger floods occurred after the ice had retreated some distance (*i. e.*, when its area was smaller), we may infer the opposite.

How soon does a glacier respond to climatic influences? This is a question which cannot be answered directly; usually we find some glaciers advancing and others retreating at the same time; for instance, a little before the middle of this century the Alpine glaciers were apparently all advancing; one after another ceased to advance and began to shorten, the number joining the retreating forces being greatest between 1850 and 1860; but it was not until 1870 that all were losing ground; for five years thereafter no glacier in the Alps was known to be advancing; in 1875, the glacier des Bossons, on Mt. Blanc, led the beginning of a new advance; since then others have joined it, until now some fifty or sixty are advancing. Peculiarities show themselves in the changes; glaciers in the same mountain group, and even glaciers so closely related as the Findelen and Gorner, near Zermatt, whose *névé* regions adjoin, are sometimes moving in opposite phases at the same time. In general there seems to be a readier response on the part of the smaller glaciers; and the steeper ones also seem to start earlier than the others; but as far as I know variations have not been analyzed according to the size, slope, height, exposure of the glaciers, etc.; in fact, it would be extremely difficult to analyze them properly without the guidance of a mathematical theory, which would enable us, when given the dimensions of a glacier, to calculate the velocity in its different parts. Material, however, is being collected which will form a basis for such a theory, in the general records of the movements of glaciers, and more particularly in the accurate observations which are annually made on the Rhone glacier under the auspices of the Swiss Alpine Club, and on some other glaciers.

M. Forel has collected and discussed the records of variations of glaciers in a series of most interesting reports to the Swiss Alpine Club.[1] He finds that glaciers go through periodic changes of from thirty-five to fifty years' duration.[2] Beginning with a glacier at its minimum the changes occur in the following order: First comes an increased velocity due to increased snow-fall, and the glacier advances rather rapidly; later the velocity diminishes, the glacier reaches its maximum, and then begins to retreat. During this whole period the rate of melting may not have changed at all markedly. The advance is rapid, taking about a third as long as the retreat, which is merely a time of melting, during a diminished flow, until a new advance, produced by increased snow-fall, begins again. The average for quite a number of glaciers observed during this century gives a complete period of thirty-eight years or more. But the subject is much complicated by the fact that different glaciers begin and end their advance at widely different times; so different indeed, that we can frequently in a given year find different glaciers representing all phases of advance and retreat. This makes the task of comparing variations of climate with variations of glaciers very difficult, for one does not know what to consider the time of maximum or minimum advance.

Some progress has however been made; Professor Brückner[3] starting with the fact that glaciers have periodic changes, made an exhaustive study of the variations in the heights of lakes, of interior seas; of the inundations of rivers, and the duration of their winter freezing; of agricultural matters, such as the times of vintage, etc., and found a similar period in them all. He then took up meteorological observations proper and found the same thing. His researches reach back to 1700. He was able

[1] Jahrbuch des Schw. Alp. Club, from 1881 to date. I am indebted to Professor Forel and Professor Richter (cited below) for almost all the material of this paper.

[2] American glaciers are in general retreating, but observations have not been frequent enough to show a periodicity in their movements.

[3] Klima-Schwankungen seit 1700. Geog. Abhand. von Dr. Penck, 1890, IV. (cited by Professor Forel).

to state that since then, and presumably before, the climate has oscillated about its mean in a period of thirty-five years. Professor Richter[1] by a careful study of the historical records of Alpine glaciers, has confirmed this, and has carried it back another hundred years. He has shown that the average period of the variations of glaciers for the last three hundred years has been the same as Brückner's period. He has also shown that during the present century the larger number of glaciers have begun to advance very soon after the beginning of a cold period of increased precipitation, though some of the larger ones have started only twenty or even thirty years later. We wish now to know the relation connecting the time of increased precipitation with the time of advance of glaciers, as a function of their size, slope, etc.

Two theories have been advanced to explain the *modus operandi* of glacial variations. Professor Richter[2] thinks that there must first be an accumulation of snow in the *névé* regions, which at last produces a great enough pressure to overcome the resistance, due to the friction against its bed, of the glacier's tongue; which is then pushed forward with a greater velocity, resulting in an advance of the glacier; this continues until the drain on the *névé* regions, on account of more rapid flow, exhausts the accumulation of snow; after this the motion almost entirely ceases, and the glacier melts back until another advance begins. Professor Forel[3] calls this the "theory of intermittent flow." and points out that according to it variations in the size of glaciers would occur entirely independently of meteorological changes. He had, in 1881, offered a "theory of continuous flow."[4] According to this theory the glacier responds immediately to increased snow-fall, but only in its upper part is there an immediate increase in velocity; this pressing forward of the ice

[1] Geschichte der Schwankungen der Alpengletscher. Zeits. des deut. u. Oest. A–V., 1891. This is a most important paper.

[2] Der Obersulzbach Gletscher, 1880–82. Zeits. des deut. u. Oest. A–V., 1883.

[3] Jahrbuch des Schw. Alp. Club, 1887–88.

[4] Bibliot. Univ. de Geneve, 1881.

from above results in a progressive thickening of the glacier from above downward. Though the increase in the thickness and velocity may have begun in the upper regions, the end may still be melting back; when, however, this increase in thickness reaches the lower end the advance will begin, for there will be a greater quantity of ice and it will have a greater velocity; it will therefore have to travel further before being melted away. After a while, the snow-fall becoming less, the glacier will gradually decrease in thickness, and consequently in velocity, until the rate of melting exceeds the rate of flow, when the retreat will begin. Comparatively small changes in snow-fall result in marked movements of the glacier's end; for not only is the thickness of the ice at the end changed, but the velocity is also, and these

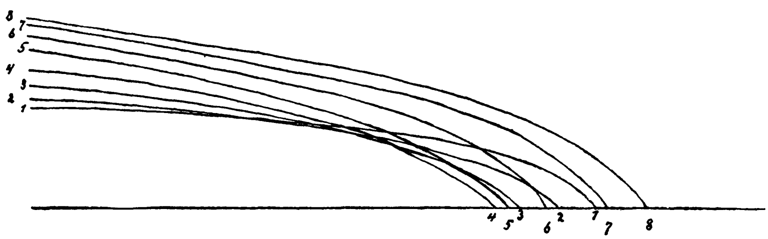

FIG. 1.

two factors so interact that an increase of one produces an increase of the other, and the reverse. This can be made clearer by a diagram.

In Fig. 1, let line 1 represent the surface of the glacier when the *névé* fields are lowest; suppose now the snow-fall increases; the *névé* fields get thicker, but the end is not affected, and it continues to melt back; the lines 2, 3, etc., represent the surface at successively later times. After a while the thickening and consequent increase in velocity of the lower end causes it to advance.

Similarly the continued advance after the snow-fall has begun to diminish, and the later retreat, may be illustrated by Fig. 2.

The question of glacial erosion is a very important one; the

geological evidence has not led geologists to a uniform opinion. We know little about the velocity below the surface of the glaciers; can we find out how rapidly glaciers are sliding over their beds? This is certainly very difficult to do; in fact the only place where observations can be made is near the end of the ice or at the sides where the movement is slow. During the last thirty or forty years, a period of retreat, the movement has been slower than it will be during the advance now beginning; observations made during the retreat would certainly lead to an underrating of the effect of a glacier on its bed; but during the more rapid movement of the advance we shall form a better estimate of it. A mathematical theory might enable us to infer

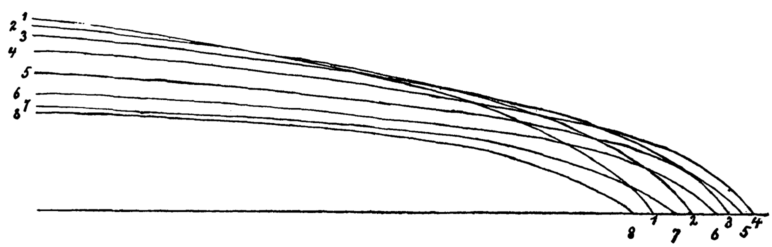

FIG. 2.

the velocity at the bottom from that at the surface; this would certainly be an immense gain in our knowledge of glaciers and ice-sheets. It is for this reason that experiments on the physical properties of ice, and observations on the rate of flow, rate of melting, and comparisons of the variations of glaciers with climatic variations, etc., are of so much importance to the glacial geologist.

The study and observations of the variations of glaciers is being pushed with great zeal by the various Alpine clubs, and the results published in their journals, where they are apt to escape the notice of American geologists. Last summer the International Congress of Geologists at Zurich appointed a committee to encourage, and to collect, observations on glaciers all over the world, with the special object in view of discovering a relation between the variations of glaciers and of meteorological

phenomena.[1] It is with the hope of enlisting the coöperation of American geologists, and others who may be willing to help, that this paper has been written.

There are a number of small glaciers in the Sierra Nevada mountains, larger ones on the old volcanoes of the Cascade Range and in British Columbia, and immense ones in Alaska. Opportunities for making observations on many of these glaciers will frequently arise, even to travelers, who, if willing, can contribute to the problem of the variations of glaciers.

There are two glaciers in North America that are so frequently visited that we should secure a very complete set of records of them; they are the Illecellewaet in the Selkirk Mountains and the Muir in Alaska. I add a short list of the observations that should be made, and the methods; many are simple, and easily made by travelers.

OBSERVATION OF GLACIERS.[2]

It is desired to obtain a general description of little known glaciers; to determine at the time a glacier is visited whether it is advancing, retreating or stationary; to determine the year of maximum advance or retreat; to collect observations of travelers which may throw light on the extension of a glacier at an earlier

[1] This committee representing various countries is as follows:

Austria: Professor Ed. Richter, Graz.
Germany: Professor S. Finsterwalder, Munich.
United States of America: Dr. Harry Fielding Reid, Baltimore.
Denmark: Dr. R. I. V. Steenstrup, Copenhagen.
France: Prince Roland Bonaparte, Paris.
Great Britain and Colonies: Captain Marshall Hall, Dorset.
Norway: Dr. A. Ojen, Christiania.
Russia: Professor Ivan Mouchketow, St. Petersburg.
Sweden: Dr. F. U. Svenonius, Stockholm.
Switzerland: Professor F. A. Forel, Morges; Dr. Leon Du Pasquier, Neuchatel.
A representative of Italy has not yet been appointed.

[2] In making out this list of observations and methods, I have had the advantage of consulting the papers of PROFESSOR FOREL in the Jahrb. des Schw. A. C., 1882–83, 1883–84, 1890–91; the instructions of PROFESSORS KILIAN and COLLET in the Annuaire de la Soc. des Tour. du Dauphine, for 1891, and the memorandum of the Alpine Club, cited below.

date; to record the extent and thickness of the glacier as often as possible; to determine the velocity of flow of the ice; to determine the rate of melting of the ice.

General description.—Name. Latitude, longitude and altitude of end. General direction of flow.

General description of glacier (Is it long or broad? Is it in a narrow valley, or on a plateau? Is it simple or made up of several tributaries? Is it smooth or much crevassed? Are there any ice-falls? Are there moraines on the ice? Altitude of *névé* line; size of *névé* fields and of tongue; a sketch map of an unsurveyed glacier is useful).

Slope of glacier.—(1) Slope of surface in different parts of the glacier; (2) estimate of slope of glacier's bed, where possible.

Old moraines.—Describe their forms, condition and distance from the glacier, if terminal, and their height above the ice, if lateral.

Lakes.—Are they true rock-basins or dammed lakes? For rock-basins determine the form of the bed by soundings, if possible.

Recent changes.—(*a*) Question anyone who may be able to give information whether the glacier has recently been larger or smaller than at present, and when it began to advance or retreat.

(*b*) Obtain photographs of the glaciers with date when taken. "The earlier recent movements of glaciers may be noted by the following signs:

"When the ice is advancing, the glaciers generally have a more convex outline, the ice-falls are more broken into towers and spires, and piles of fresh rubbish are found shot over the grass of the lower moraines. Moraines which have been comparatively recently deposited by advancing ice are disturbed, show cracks, and are obviously being pushed forward or aside by the glacier.

"When the ice is in retreat, the marks of its further recent extension are seen fringing the glacier both at the end and sides in their lower portions; the glacier fails to fill its former bed, and bare stony tracts, often interspersed with pools, or lake-

lets, lie between the end of the glacier and the mounds of recent terminal moraines."[1]

Future changes.—For this purpose all records of the extent and thickness of the ice at date of observation are useful.

The position of the end may be recorded as follows:

(*a*) Measure distance of one or more points of the glacier's end from cairns or prominent rocks, which should be marked by paint or chisel. Or, take magnetic bearings of a tangent to the end of the glacier from a station on the valley's side; this tangent should be about at right angles to the direction of the valley.

(*b*) Photographically.—(1) All photographs of the end of the glacier are useful; particularly if the magnetic bearings of the camera, and the approximate distance from the glacier are given. (2) Select two stations, one on each side of the valley, commanding a view of the glacier's end. Photograph the end from these two stations; two photographs from each station may be required to show all the end. Mark the stations, describe them carefully and leave an account at the ranch or hotel from which the glacier is usually visited so that they can easily be found by later observers, who should take photographs from these points in preference to all others. This will be the beginning of a systematic record of the glacier. From these photographs it will be possible to make a map of the glacier's end if we know: the distance between the stations; the angle at each station between the other and some point in each photograph and the focal length of the lens, or the angles at each station between the other and two points in each photograph, not less than half the length of the plate apart; the bearings of these two points will enable us to determine both the direction in which the camera was pointed and the focal length of the lens.

An observer, provided with a small theodolite (or even a prismatic compass) should measure from each of the stations the angle between the other and all prominent peaks or other points likely to appear in the photographs, and should determine the distance between the stations. This need only be

[1] Memorandum on Glacier Observations, issued by the Alpine Club, June, 1893.

done once, after which all earlier and future photographs taken from these stations can be used to mark accurately on the map the glacier's end at the date they were taken. If vertical angles also are measured, and the difference in altitude of the stations determined, contour lines can be added to the map. This method yields the greatest amount of information for the least amount of trouble.

The stations should be selected so as to be as easily accessible and recognizable as possible; the distance between the glacier's end and the line joining them should be between one-seventh and twice their distance apart; nearer the former if the glacier is retreating, nearer the latter if it is advancing.

In taking the photograph have the camera as level as possible, with the plate vertical; do not use the swing back, and do not alter the focus in taking two or more pictures from the same station. Hand cameras should rest on some support; a rock answers well. The longer the focal length of the lens, the better; negatives or positives on glass yield more accurate results than prints, as the paper may become distorted in the manipulation.

Variations of thickness.—(*a*) Select a station on the side of the glacier's valley. Mark it. Select a direction about at right angles to the glacier and record it by compass bearing or by the angle it makes with some easily recognizable point. Determine by aneroid barometer the difference in level between the station and the following points on this line: (1) the sides of the glacier; (2) the highest point of the glacier; (3) any other points feasible. If possible record the difference in level between station and the end of the glacier or some base station.

(*b*) Observe by aneroid or measure the vertical distance between some easily recognizable point in the *névé* region, such as a projecting rock, and the glacier's surface at its side. If possible note difference of level between this station and some base station.

Velocity of flow.—Persons provided with instruments can readily determine the velocity of flow by sighting on a line of stakes or on some prominent bowlders at intervals of a few days.

Another method, which yields average velocities, is to determine the position on the ice of some prominent bowlder which is marked, so that it can be recognized after one or more years, and the distance it has moved measured. A very good way is to lay out a line of sheet-iron plates, say, three inches square, on which is painted the date when, and the position where, they are placed. These will sink slightly into the ice, will not be blown away by the wind, and will not roll or slip, as bowlders may. They can be recovered and the distance moved over determined by a future observer. Stones are used in this way for the observations on the Rhone glacier.

Rate of melting.—At the lower end of glaciers, when the ice is somewhat disintegrated and will not in general hold water, the melting can be measured by boring an auger hole in the ice and putting a stick in it; the apparent rise of the stick out of the ice will be the measure of the melting. If the ice is compact enough to hold water, this method may yield inaccurate results; it is better then to bore two holes starting from the same point on the surface of the ice and making an angle with each other of 45° to 60°, put a stick in each hole and where they cross bind them firmly together with wire. The ice will melt around the sticks, but each will prevent the other from sinking into its deepened hole. The wire may be used as an index, and its increasing height above the ice will measure the melting.

All photographs and observations sent me[1] will be carefully filed away and preserved as the record of the history of the glacier in question; they will be considered as the property of the Geological Society of America. A poor photograph is much better than none. Prints should be mounted on linen or unmounted. On each should be marked the glacier depicted the date, the station from which the picture was taken, the direction in which the camera was pointed and whether or not the lens used was rectilinear (or give the name of the lens). If its focal length is known, it should also be given.

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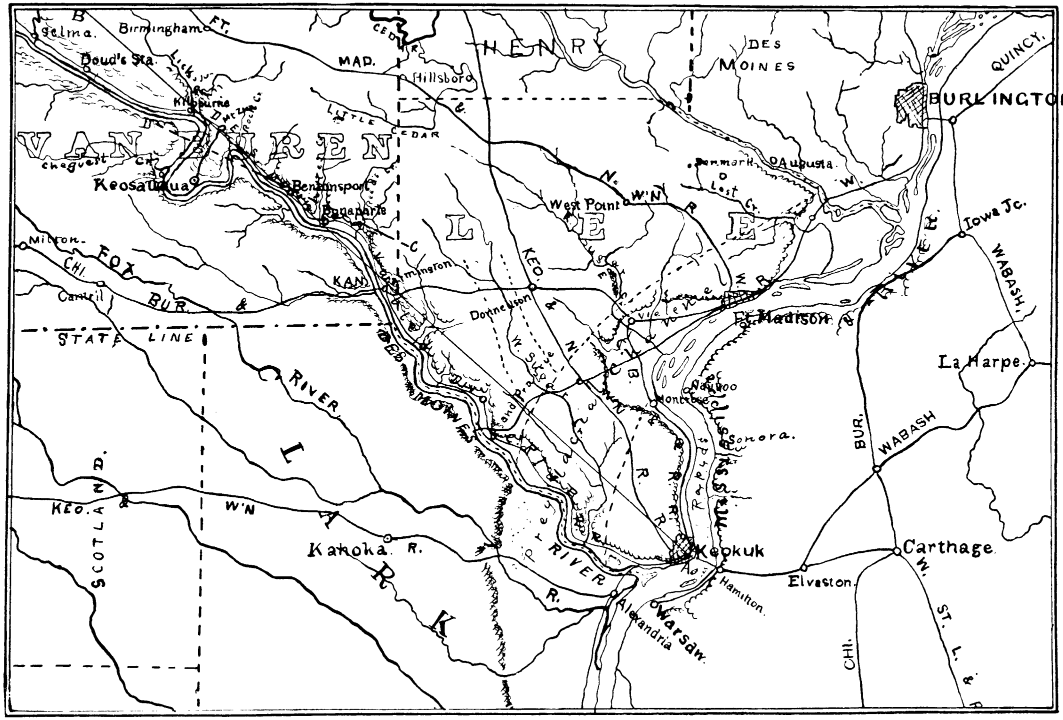

SKETCH MAP OF SOUTHEASTERN IOWA.